

## **Air-Sea and Lateral Exchange Processes in East Indian Coastal Current off Sri Lanka**

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### **LONG TERM GOAL**

The long-term goal of our research program is to understand small-scale and mesoscale oceanic dynamics around Sri Lanka and their role in the air-sea interaction processes of Bay of Bengal (BOB), in particular those related to monsoons. Oceanography around Sri Lanka is crucial for vertical and lateral mixing in BOB and exchange of water masses between the Arabian Sea and BOB. The research is conducted in the context of ASIRI initiative as well as potential future ONR initiatives in Indian Ocean.

### **OBJECTIVES**

- Understanding barriers to the predictability of North Indian Ocean circulation and monsoon breaks.
- Characterizing hydrographic data sets. Virtually no hydro-physical information is available for Sri Lankan coastal waters, including currents, temperature, salinity and optical characteristics.
- Understanding the role of the southern branch of East-Indian coastal current (the Sri Lankan current) in water exchange between the Bay of Bengal and Arabian Sea. Also of interest is the interaction of mesoscale and sub-mesoscale phenomena, and their role in determining air-sea fluxes.
- Help capacity building for Sri Lankan scientists, *e.g.*, PhD training for young scientists, assistance with implementation of models, help in acquiring new instruments, access to global data sets (*e.g.*, ARGO floats) and developing a repository of new data as a part of the ASIRI Project.

### **APPROACH**

We will conduct measurements in Sri Lanka coastal waters using the Sri Lankan R/V Samudhrika and in the northern BOB using the R/V Roger Revelle. The former will be carried out every two months in conjunction with scientists at the Sri Lanka National Aquatic Resources Research and Development Agency (NARA) along selected tracks of southeastern and eastern Sri Lanka, extending from near-shelf to deep-ocean within the Sri Lankan EEZ. The measurement program will include CTD, Rosette samplers, fluorometers, ADCP and vertical microstructure profilers. For the latter, we will be a part of the 1<sup>st</sup> leg of ASIRI Pilot Cruise, November 10-27, 2013.

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The capacity building component includes providing of training for Sri Lankan scientists and technicians at University of Notre Dame in analyzing ADCP and microstructure measurements as well as using oceanographic profilers and meteorological instruments.

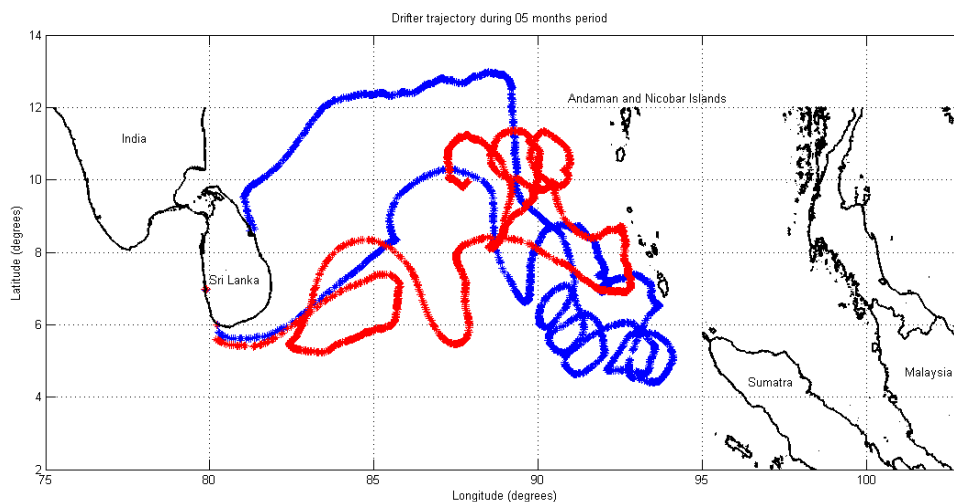
## WORK COMPLETED

During the first nine months of the project, substantial efforts have been made to equip the Sri Lankan R/V Samudhrika with modern oceanographic instrumentation and to train NARA scientists. A Seabird SBE-25plus CTD oceanographic profiler and a fluorometer have been purchased and shipped to NARA, together with a refurbished VMP profiler for the measurements of temperature microstructure and the kinetic energy dissipation rate. Testing of CTD and VMP were conducted in late August 2013, and the results are pending. A visit was made to Sri Lanka in July 2013 to discuss ASIRI scientific plans with the NARA scientists and to iron out the details of the measurement program in Sri Lanka EEZ.

Mr. Priyantha Jinadasa from NARA spent 4 months at University of Notre Dame (April-July) to receive training in ADCP data processing and to conduct research on internal waves and turbulence in shallow waters. Given that ASIRI measurements are still unavailable, the data obtained under our previous ONR project in the East China Sea were used. It was found that the modified log-layer model (Perlin et al. 2004) that accounts for the stable stratification in BBL is also adequate to describe rotating tidal currents. Higher order moments and intermittency of oceanic turbulence were also studied using this data set. Mr. Upul Adhikari from NARA also visited Notre Dame for one month training.

On August 25<sup>th</sup> 2012, NARA scientists launched, in Sri Lankan waters, several surface drifters provided by Dr. Luca Centurioni (SIO). Their trajectories in BOB were monitored and interpreted.

Air-sea fluxes at certain buoy locations of the Indian Ocean were analyzed in the context of atmospheric stability to determine how vertical mixing at the top of the sub-cloud layer controls the direction of air-sea fluxes. A strong correlation was noted. This work was conducted in cooperation with Dr. G.S. Bhat from Indian Institute of Sciences.



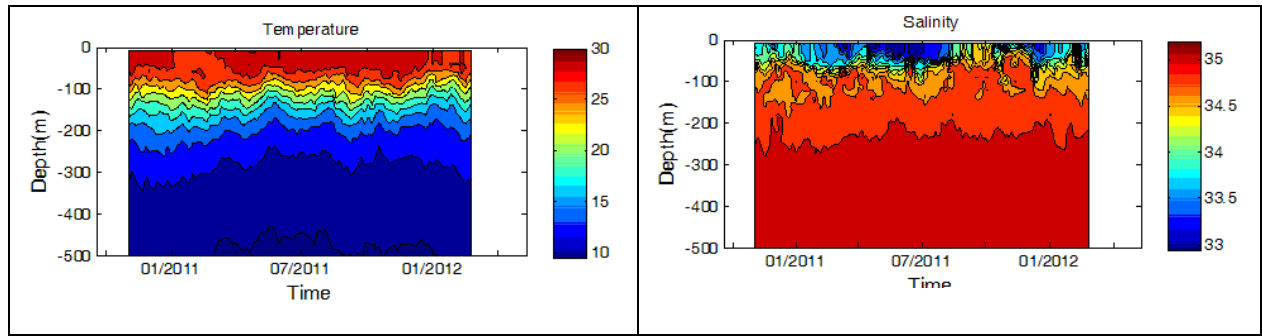
**Figure 1. Trajectories of two surface drifters launched in Sri Lanka waters**

## RESULTS

### A. Activities Related to BOB

The analysis of two surface drifters launched in Sri Lanka coastal waters showed complex behavior of surface currents to the east of Sri Lanka (Fig. 1). Two and a half loops of the red-colored drifter trajectories around  $10^\circ\text{N}$  are associated with inertial oscillations, but a characteristic period of similar loops of the blue drifter between  $4^\circ\text{N}$  and  $6^\circ\text{N}$  do not correspond to local inertial period. It is interesting that the basin-scale circulation, especially eddying motions in the southern part of BoB, forced the blue drifter to return to the Sri Lankan coast after several months. The separation of drifters from each other to follow completely different paths signifies the chaotic advection patterns in BOB, possibly introduced by the mesoscale eddy features.

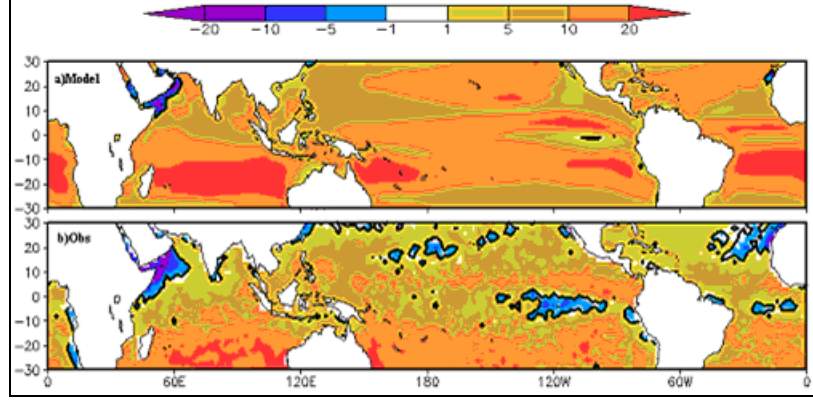
We also conducted a preliminary analysis of AGRO buoys in the region to better understand the nature of stratification in the active upper layer of BoB to help plan future microstructure measurements. The sections along the trajectory of AF286 between  $8^\circ$  and  $10^\circ\text{N}$  in the southern BoB are shown in Fig. 2. It appears that the main mesoscale activity associated with eddies and internal waves are contained to depths up to 200 m, and the fresh water impact ( $S < 33$  psu) does not penetrate more than 100 m from the surface. We plan to focus on the upper 200 m layer during our measurement program.



*Figure 2. Temperature (left) and salinity (right) sections in BoB based on the ARGO float #286 data*

### B. Activities Related to Tropical Oceans

The difference  $DT$  between the sea surface temperature (SST) and that of the air above ( $T_a$ ) is an important attribute of air-sea interactions.  $DT$  is positive over the tropical oceans except in a few climatically important regions (Fig. 3a,b).



**Figure 3: July-August average  $Q_s$  over the tropical oceans.  $Q_s$  is positive when heat flows from water to air. Color shades refer to  $Q_s$  in  $W m^{-2}$  units, and the thick black line is the  $Q_s=0$  contour, with the area enclosed regions with  $Q_s<0$ . (a) GFDL Model AR4 runs. (b) ICOADS (NOAA) observations.**

No past studies have shed light on how a negative  $DT$  can be sustained over open oceans, and we conducted a detailed study in this regard. The key factor is the heat flux ( $Q_t$ ) derived from the entrainment of higher entropy air from the layer above the atmospheric mixed layer in a regime of gradient Richardson number ( $Ri_g$ )  $>0.25$ , which is traditionally considered stable but it can become unstable under special conditions (Strang & Fernando 2001). This instability occurs when a turbulent mixed layer is capped by a stably stratified layer that has strong wind shear. A theoretical critical  $Ri_g$  for instability for this configuration does not exist, although experiments suggest a value around unity. Field data show that cases with  $0.25 < Ri_g < 1$  occur in areas exhibiting  $DT < 0$ , yielding  $Q_t$  large enough to manifest a heat flux from the atmosphere to ocean. The fidelity of  $DT$  simulated by present climate models is very poor, and a new parameterization scheme for  $Q_t$  was proposed based on our work, incorporation of which in coupled climate models (CCMs) may improve their ability to simulate  $DT$  and air-sea fluxes.

### C. Activities Related to East China Sea – Bottom Boundary Layer Dynamics

The classical Prandtl-Karman logarithmic layer velocity profile  $U(\zeta) = (u_* / \kappa) \ln(\zeta / \zeta_0)$  [standard notations is used here] is valid for a steady, unidirectional, fully developed and non-stratified parallel shear flow. Application of this model to ocean BBL usually leads to an overestimation of friction velocity, due, possibly, to the influence of form drag (Sanford and Lien 1999), rotation of the flow vector (Lozovsky et al. 2008) and stratification (Perlin et al. 2005). To gain further insights, we explored the (ADCP) velocity profiles from the Korean sector of the East China Sea obtained during our previous grant, using the approach of Perlin et al. (2005).

The principal novelty of the modified log-layer model (MLL) is the introduction of an empirical formula for the turbulent length scale

$$l_{BL} = \kappa \zeta \left( 1 - \frac{\zeta}{h_d} \right) . \quad (1)$$

It combines the classical scale  $l_c = \kappa \zeta$  that grows linearly with height  $\zeta$  from the seafloor in non-stratified waters with the buoyancy (or Ozmidov) scale  $L_N = \varepsilon^{1/2} / N^{3/2}$ , which takes over  $l_c$  near the

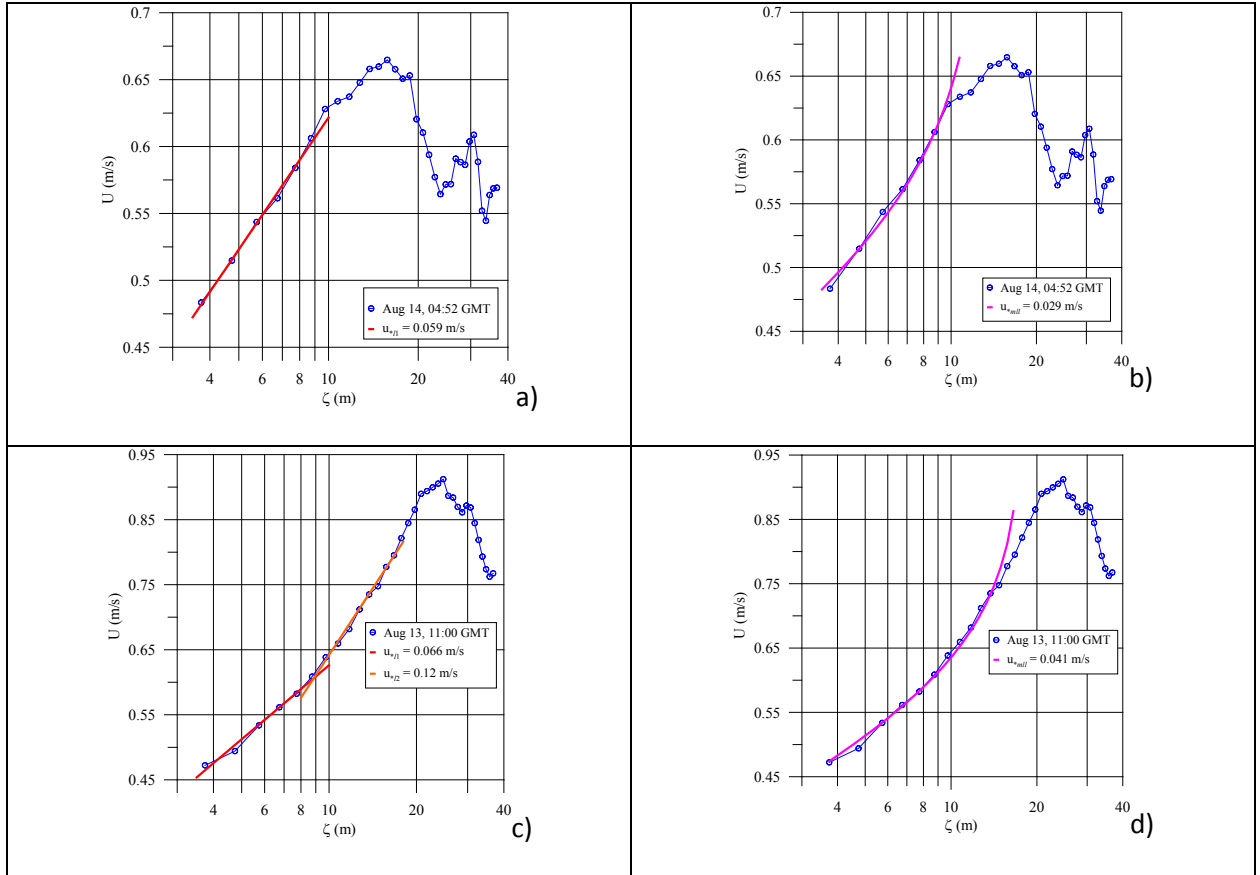
upper boundary of BBL,  $h_{BL}$ , where the sizes of turbulent eddies generated by boundary stress start to decrease as a result of turbulence suppression by stable stratification. Eq. (1) is to be applicable between  $\zeta = 0$  and a critical height  $\zeta = h_d$ , where

$$h_d = \frac{h_{BL}}{1 - (L_N / \kappa h_{BL})}. \quad (2)$$

The constant momentum flux parameterized by  $u_*^2 = K(dU/d\zeta)$  leads to the MLL velocity profile,

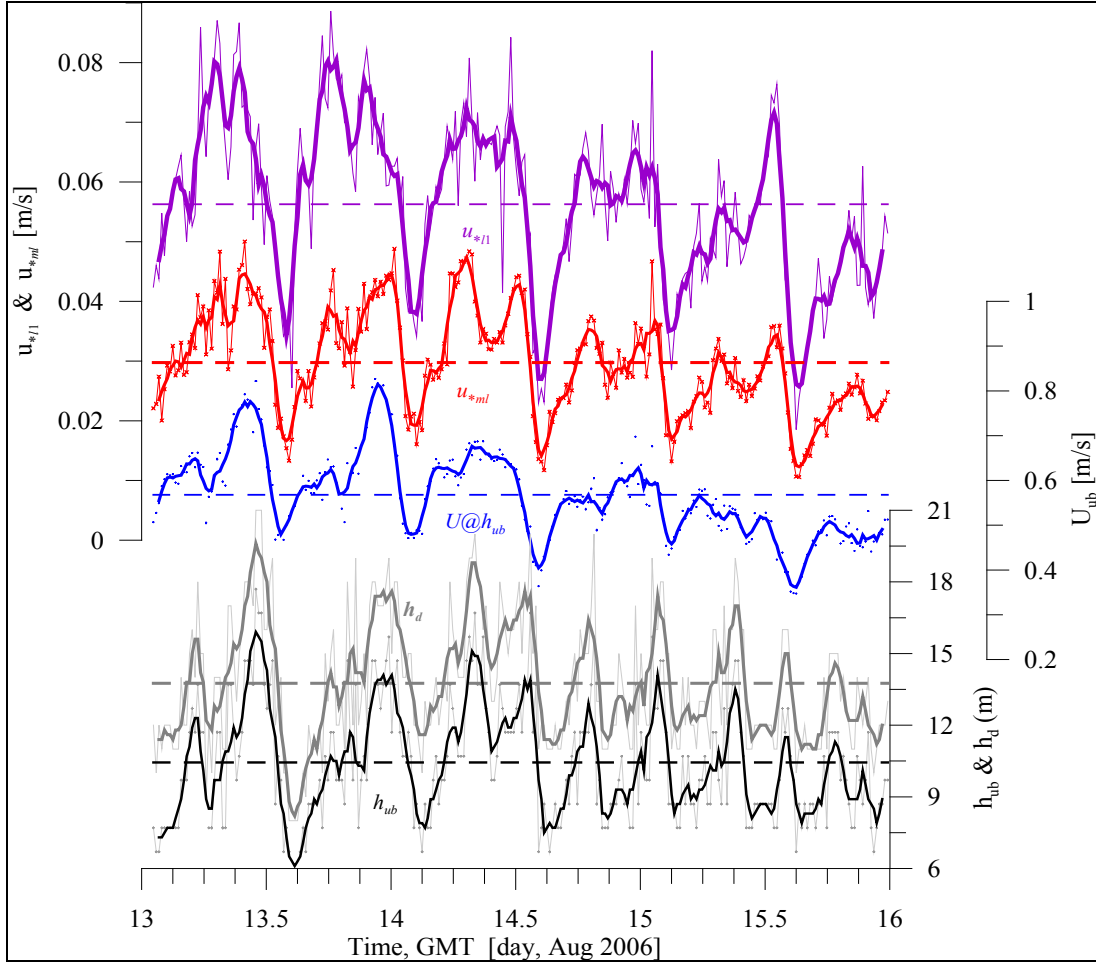
$$U(\zeta) = \left( \frac{u_*}{\kappa} \right) \ln \left( \frac{\zeta(h_d - \zeta_0)}{\zeta_0(h_d - \zeta)} \right), \quad (3)$$

if the classic turbulent scale  $l_{tr} = l_c = \kappa\zeta$  is substituted by  $l_{tr} = l_{BL}$  (Eq. 1) in the eddy diffusivity formulation  $K = u_* l_{tr}$ . Eq. (3) was employed to calculate the modified friction velocity  $u_* \equiv u_{*ml}$  by fitting 270 measured ADCP profiles using the Matlab cftool capability. The height  $h_d$  was treated as an adjustable parameter that varied in the range 8 – 21 mab. The MLL model successfully approximates both the single and double log-layer profiles, giving, as a result, substantially lower values for the friction velocity compared to the classic log-layer model. Some typical fitted  $U(\zeta)$  profiles are shown in Fig. 4.



**Figure 4. Comparison of single (a) and double (c) log-layer fittings to the East China Sea data. MLL approximations (Eq. 3) for (a) and (c) are shown in (b) and (d), respectively.**

Time variations of the modified friction velocities  $u_{*mll}(t)$  obtained via Eq. (3) are compared in Fig. 5 with the friction velocity  $u_{*ll}(t)$  deduced from the classical log-layer. The upper boundary of the modified log-layer  $h_{ub}(t)$ , the critical height  $h_d(t)$  [Eq. 2], and the mean velocity  $U_{ub}(t)$  at  $\zeta = h_{ub}$  are also shown in Fig. 5. It is clear that both estimates of the friction velocity are subjected to same basic oscillations as the mean current  $U_{ub}(t)$ . Interestingly, the quarter diurnal periodicity is more pronounced in  $u_{*mll}(t)$  compared to  $u_{*ll}(t)$ , and the amplitude of  $u_{*mll}(t)$  semidiurnal component is smaller than that of  $u_{*ll}(t)$ . Specifically, the difference is evident during the phases of low  $U_{ub}(t)$ , whence the minima of  $u_{*ll}(t)$  are much pronounced than those of  $u_{*mll}(t)$ , which possibly indicates a more stable and robust modified friction velocity estimates. The most important result, however, is that the absolute values of  $u_{*mll}(t)$  became about two times smaller than  $u_{*ll}(t)$ , which leads to reasonable estimates of the drag coefficient  $C_{Dm} = u_{*mll}^2 / U_A^2$  in accordance with the classical estimates. Here  $U_A$  is properly specified amplitude of the mean current,



**Figure 5. Time series of the friction velocity in the classic logarithmic layer  $u_{*ll}$  and in the modified logarithmic layer (MLL)  $u_{*mll}$  vis-à-vis the velocity magnitude at the upper boundary of MLL  $U@h_{ub}$ . The mean values of all variables for the period of observations are shown by the horizontal dashed lines.**

The variations of  $h_{ub}(t)$  and  $h_d(t)$  are well correlated, being swayed by semi and quarter diurnal tidal harmonics as well as higher frequency oscillations. The difference between the means  $\Delta h = \langle h_d \rangle - \langle h_{ub} \rangle = 13.8 - 10.4 = 3.4$  m is similar to that reported by Perlin et al. (2005) for the Oregon shelf data.

Formal linear regression of  $u_{*ll}$  vs.  $u_{*ml}$  (not shown) suggests that for an expeditious estimate of the friction velocity, the classic log-layer model ( $u_{*ll}$  estimates) can be used as a proxy for MLL friction velocity  $u_{*ml}$ , but the latter is smaller by a factor about two (1.85); the averaged  $\langle u_{*ml} \rangle = 2.9 \times 10^{-2}$  m/s while  $\langle u_{*ll} \rangle = 5.3 \times 10^{-2}$  m/s. All these indicate that the stratification, specifically near the upper boundary of BBL that indirectly affects MLL (through  $h_d$  and hence the buoyancy scale  $L_N$ ) is an important factor of the BBL dynamics. This should not be ignored in the analysis of turbulence characteristics and mixing in tidal boundary layers in shallow waters.

## IMPACT/APPLICATION

Our research program involves collaboration between the US, Sri Lankan and Indian scientists as well as other international groups (Russia, Spain). One paper on the study of turbulence in SCS has been accepted for publication in the Journal of Ocean Dynamics, and two other papers on turbulence intermittency and mixing efficiency have been published in Physica Scripta and Phil. Trans. Roy. Soc. A. Dr. Priyantha Jinadasa (NARA) visited University of Notre Dame in April-July 2013 for training and conducting joint work with the PIs. This helped capacity building and planning for a joint measurement program in Sri Lankan waters under the current ASIRI DRI. Because of the Sri Lankan component of ASIRI, it was possible to reach out to Seychelles to initiate new collaboration that will allow future studies in the equatorial Indian Ocean, including equatorial, east African, Mozambique/Mascarene and the Agulhas current systems.

## TRANSITIONS

None

## RELATED PROJECTS

The PIs has another ONR-PO funded project on East China Sea, which will expire in 2013.

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